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Surface Fatigue Life of High Temperature Gear Materials

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SURFACE FATIGUE LIFE OF HIGH TEMPERATURE GEAR MATERIALS

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Abstract

Three high temperature gear materials were evaluated using spur gear surface fatigue tests. These materials were, VASCO max 350, VASCO matrix II, and nitralloy N and were evaluated for possible use in high temperature gear applications. The fatigue life of the three high temperature gear materials were compared with the life of the standard AISI 9310 aircraft gear material. Surface fatigue tests were conducted at a lubricant inlet temperature of 321 K (120 °F), a lubricant outlet temperature of 350 K (170 °F), a maximum Hertz stress of 1.71 GPa (248 ksi), a speed of 10 000 rpm and with a synthetic paraffinic lubricant. The life of the nitralloy N was approximately the same as the AISI 9310, the life of the VASCO max 350 was much less than the AISI 9310 while the life of the VASCO matrix II was several times the life of the AISI 9310. The VASCO max 350 also showed very low fracture toughness with approximately half of the gears failed by tooth fracture through the fatigue spall. The VASCO matrix II had approximately 10-percent fracture failure through the fatigue spalls indicating moderate to good fracture toughness.

Introduction

Aircraft turbine engine requirements are increasing the demand for higher operating temperature in several advanced and high power density applications for gears and rolling element bearings. The surface temperature of power gearing normally operates considerably higher than the bulk oil temperature; thereby, requiring a more temperature resistant gear material that will provide long life at these high temperature operating conditions. Previous testing with rolling element bearings[1] has shown that at high stress loads the surface fatigue life of bearings is much longer when the surface hardness at the operating temperature is Rockwell Rc 58 or higher and is drastically reduced when the hardness is less than Rc 58.

Several high-hot hardness carburized grade steels have been developed for bearing and gearing in recent years. Bearing and rolling contact fatigue tests have shown very good surface fatigue life with some of these new high temperature materials.[2]

Hot hardness testing of several high temperature steels were conducted[3,4] to determine their short term and long term hot hardness and their potential for use as high temperature bearing and gear steels. High temperature gear tests have been conducted with several gear materials.[5,6] Two nitriding materials that have shown promise for moderate to high temperatures were nitralloy N and super nitralloy (5Ni2Al). Nitralloy N was used[7] to conduct scoring tests up to 644 K (700 °F) with a bulk oil temperature of 477 K (400 °F). The hot hardness tests with super nitralloy, 5Ni2Al,[3] have shown that it maintains a usable hot hardness up to 505 K (450 °F). Nitralloy N would be expected to have a hot hardness a little lower than super nitralloy since it has 1.5 percent less nickel. Fatigue tests were conducted with gears manufactured from super nitralloy, 5Ni2Al,[8] which showed a fatigue life that was comparable to AISI 9310.

Hot hardness testing with VASCO matrix II[3] shows that it maintains a usable hot hardness in excess of 644 K (700 °F). This material is through hardened similar to high strength tool steels such as AISI M–50. VASCO matrix II is an age hardening high temperature material that is aged at 769 K (925 °F) to have a hardness of Rc 60 through precipitation hardening in a martensite matrix structure.

Rolling contact tests were conducted in a RC (rolling contact) machine[2] with VASCO matrix II and VASCO max 350. In these tests the VASCO matrix II had rolling contact fatigue life equivalent to M50 while the VASCO Max 350 Rc fatigue life was considerably less.

The objective of the research work reported in this paper was to compare under closely controlled test conditions the fatigue lives and failing modes of test spur gears made of nitralloy N, VASCO max 350, and VASCO matrix II and compare the results with the standard aircraft gear material AISI 9310.

Test Gears and Materials

The test gears used in the tests reported herein are shown in Fig. 1. Dimensions for the test gears are summarized in Table 1. All gears had a minimal surface finish on the tooth flank of 0.406 μm cla (16 μin. cla) and a standard 20° involute tooth profile with a small profile tip relief.

The test gears were manufactured from three materials. These were consumable electrode vacuum melted (CVM) VASCO max 350, CVM VASCO matrix II, and nitralloy N AMS 6475D. The test results were compared with gears

manufactured from CVM AISI 9310 AMS 6265H. The chemical composition of these materials are given in Table 2.

The gears manufactured from the nitralloy N material were case nitrided and hardened to a Rockwell hardness of Rc 63 with a case depth of 0.046 to 0.051 cm (0.018 to 0.020 in.) and with a core hardness of Rockwell Rc 41. Photomicrographs of the case and core of the nitralloy N gears are shown in Figs. 2(a) and (b).

The VASCO max 350 gears were finish machined to allow for 25×10^{-4} cm (0.001 in.) shrinkage during age hardening. They were then age hardened at 760 to 777 K (910 to 940 °F) for 3 hr and allowed to air cool for a case hardness of Rockwell Rc 59 and a core hardness of Rockwell Rc 57.5. Photomicrographs of the case and core of the VASCO max 350 are shown in Figs. 2(c) and (d).

The gears manufactured from VASCO matrix II were hardened after rough machining by austenetizing at 1380 to 1390 K (2020 to 2040 °F) for 15 min, quench in a salt bath at 880 K (1125 °F) and air cool to room temperature. They were then triple tempered (2 + 2 + 2 hr) at 811 to 825 K (1000 to 1025 °F) as soon as the steel had cooled to 311 to 339 K (100 to 150 °F) from the quench. Photomicrographs of the case and core of the VASCO matrix II are shown in Figs. 2(e) and (f).

The gear pitch diameter was 8.89 cm (3.5 in.). Table 3 lists the heat treatment procedure for the different groups of gears tested including AISI 9310. Each group of gears was tested to fatigue failure by surface pitting under identical test conditions. These test conditions included a gear temperature of 350 K (170 °F), a maximum Hertz stress of 1.71 GPa (248 ksi), and a speed of 10 000 rpm.

Apparatus and Procedure

Gear Test Apparatus

The gear fatigue tests were performed in the NASA Lewis Research Center's gear test apparatus (Fig. 3(a)). This test rig used the four-square principle of applying the test gear load so that the input drive only needs to overcome the frictional losses in the system.

A schematic of the test rig is shown in Fig. 3(b). Oil pressure and leakage flow are supplied to the load vanes through a shaft seal. As the oil pressure is increased on the load vanes inside the slave gear, the loop torque is applied. This torque is transmitted through the test gears back to the slave gear, where an equal but opposite torque is maintained by the oil pressure. This torque on the test gears, which depends on the hydraulic pressure applied to the load vanes, loads the gear teeth to the desired contact or Hertz stress level. The two identical test gears can be started under no load, and the load can be applied gradually, without changing the running track on the gear teeth.

Separate lubrication systems are provided for the test gears and the main gearbox. The two lubrication systems are separated at the gearbox shafts by pressurized labyrinth seals. Nitrogen is the seal gas. The test gear lubricant is filtered through a 5-μm-nominal fiberglass filter. The test lubricant can be heated electrically with an immersion heater. The temperature of the heater is controlled to prevent overheating the test lubricant.

A vibration transducer mounted on the gearbox is used to automatically shut off the test rig when a gear surface fatigue occurs. The gearbox is also automatically shut off if there is a loss of oil flow to either the main gearbox or the test gears, if the test gear oil overheats, or if there is a loss of seal gas pressurization.

The belt-driven test rig can be operated at several fixed speeds by changing pulleys. The operating speed for the test reported herein was 10 000 rpm.

Test Lubricant

All the gears were lubricated with a single bath of synthetic paraffinic oil. The physical properties of this lubricant are summarized in Table 4. Five percent of an extreme-pressure additive, designated Lubrizol 5002 (partial chemical analysis given in Table 4), was added to the lubricant.

Test Procedure

After the test gears were cleaned to remove the preservative, they were assembled on the test rig. The 0.635-cm (0.25-in.) wide test gears were run in an offset condition with a 0.30-cm (0.12-in.) tooth-surface overlap to give a load surface on the gear face of 0.28 cm (0.11 in.), thereby allowing for the edge radius of the gear teeth. If both faces of the gears were tested, four fatigue tests could be run for each set of gears. The gear tooth test temperature was low enough to prevent one test from affecting the other test with the same gear. All tests were run in at a pitch-line load of 1225 N/cm (700 lb/in.) for 1 hr, which gave a maximum Hertz stress of 0.756 GPa (111 ksi). The load was then increased to 5784 N/cm (3305 lb/in.), which gave a pitch-line maximum Hertz stress of 1.71 GPa (248 ksi) if plain bending is assumed. However, because there was an offset load, an additional stress was imposed on the tooth bending stress. Combining the bending and torsional moments gave a maximum stress of 0.26 GPa (37 ksi). This bending stress does not include the effects of tip relief, which would also increase the bending stress.

Operating the test gears at 10 000 rpm gave a pitch-line velocity of 46.55 m/sec (9163 ft/min). Lubricant was

supplied to the inlet mesh at 800 cm^3/min (0.21 gpm) at 321 K (120 °F) The lubricant outlet temperature was nearly constant at 350 K (170 °F). The tests ran continuously (24 hr/day) until they were automatically shut down by the vibration detection transducer, located on the gearbox adjacent to the test gears. The lubricant circulated through a 5-m fiberglass filter to remove wear particles. After each test the lubricant and the filter element were discarded. Inlet and outlet oil temperatures were continuously recorded on a strip-chart recorder.

The pitch-line elastohydrodynamic (EHD) film thickness was calculated by the method of Ref. 9. It was assumed, for this film thickness calculation, that the gear temperature at the pitch line was equal to the outlet oil temperature and that the inlet oil temperature to the contact zone was equal to the gear temperature, even though the inlet oil temperature was considerably lower. It is possible that the gear surface temperature was even higher than the outlet oil temperature, especially at the end points of sliding contact. The EHD film thickness for these conditions was computed to be 0.33 μm (13 μin.), which gave an initial ratio of film thickness to composite surface roughness, λ of 0.55 at the 1.71 GPa (248 ksi) pitch-line maximum Hertz stress.

Results and Discussion

One lot each of CVM VASCO max 350, VASCO matrix II, and nitralloy N spur gears were tested in pairs until failure or were suspended after 500 hr of testing without failure. Twenty or more gears were tested in each lot. Test conditions were a tangential load of 6364 N/cm (3634 lb/in.), which produced a maximum Hertz stress of 1.71 GPa, (248 ksi). The test gears failed either by pitting and or tooth fracture. Test results were analyzed by considering the life of each pair of gears as a system. The pitting fatigue life results of these tests are shown using the Weibull plots of Fig. 4 and are summarized in Table 5. These data were analyzed by the method of Johnson.[10]

A Weibull plot of the surface-pitting fatigue life of the CVM VASCO max 350 gears is shown in Fig. 4(a). A typical fatigue spall is shown in Fig. 5(a). Several of the VASCO max 350 gears failed by tooth fracture either before or after a fatigue spall. A typical tooth fracture for these gears is shown in Fig. 6(a). The tooth fractures that failed after a fatigue spall were treated as surface fatigue failures while those that failed without a fatigue spall were treated as suspensions. There were two tests that ran for 500 hr without failure and these were also treated as suspensions. The 10- and 50-percent surface fatigue lives of the VASCO max 350 test gears are shown in the Weibull plot of Fig. 4(a) and Table 5 and was 2 million and 15 million stress cycles, respectively. These lives are considerably less than the standard AISI 9310 test gears which have a 10- and 50-percent surface fatigue of 20 million and 45 million cycles respectively. The confidence number for the life difference between the VASCO max 350 and AISI 9310 was 99 percent which indicates that the life difference is statistically significant. The confidence number indicates the percentage of time the order of the test results would be the same. For a confidence number of 99 percent, 99 out of 100 times the test is repeated the gear life difference for the two materials would be the same. Experience has shown that a confidence number of 80 percent or greater would indicate a meaningful life difference.

A Weibull plot of the surface pitting fatigue life of the VASCO matrix II gears is shown in Fig. 4(b). There were 33 fatigue tests run with this material, 11 of which ran for 500 hr without failure. A fatigue spall for this material is shown in Fig. 5(b). There were two gear tests that resulted in broken teeth for this material after running for some time with a fatigue spall. Figure 6(b) shows a typical tooth fracture through the fatigue spall for this material. The 10- and 50-percent surface fatigue lives of the VASCO matrix II test gears are shown in the Weibull plot in Fig. 4(b) and Table 5 and were 141 million and 287 million stress cycles, respectively. These lives were approximately 7 times the life of the standard AISI 9310 gears and more than 20 times the life of the VASCO max 350. The confidence number for the life difference between the VASCO matrix II and the AISI 9310 was 99 percent which indicates that the life difference is statistically significant.

The surface pitting fatigue life of the nitralloy N (AMS 6475D) is shown in the Weibull plot of Fig. 4(c). A typical fatigue for these gears is shown in Fig. 5(c). There were 23 surface fatigue tests conducted with the nitralloy N gears all of which resulted in surface fatigue spalls. The 10- and 50-percent surface fatigue lives of the nitralloy N are shown in the Weibull plot of Fig. 4(c) and Table 5 and was 19 million and 39 million stress cycles, respectively. The surface fatigue life of the nitralloy N was only slightly less than the life of the AISI 9310 and would be statistically equal to the life of the AISI 9310 gears. The confidence number for the life difference between the nitralloy N and AISI 9310 was 50 percent which means that the life difference is not statistically significant.

Summary of Results

Three groups of carburized, hardened, and ground spur gears manufactured from one heat each of CVM VASCO max 350, CVM VASCO matrix II, and nitralloy N (AMS 6475D) were evaluated using spur gear surface fatigue tests. These materials were evaluated for possible use in high temperature gear applications and were compared with one group of the standard aircraft gear material CVM AISI 9310 AMS 6265H.

Surface fatigue tests were conducted at a lubricant inlet temperature of 321 K (120 °F), a lubricant outlet

temperature of 350 K (170 °F), a maximum Hertz stress of 1.71 GPa, a speed of 10 000 rpm and with a synthetic paraffinic lubricant. The following results were obtained.

1. The 10-percent life of the nitralloy N was approximately the same as the AISI 9310.

2. The 10-percent life of the VASCO max 350 was approximately one-tenth of the life of the standard AISI 9310.

3. The 10-percent life of the VASCO matrix II was approximately seven times the life of the standard AISI 9310.

4. The VASCO max 350 demonstrated very low fracture toughness with approximately one-half of the gears failing by tooth fracture through a fatigue spall.

5. The VASCO matrix II had approximately 10-percent fracture failure through a fatigue spall indicating moderate to good fracture toughness.

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TABLE 1.—SPUR GEAR DATA

[Gear tolerance per AGMA class 12.]

Number of teeth	28
Diametral pitch	8
Circular pitch, cm (in.)	0.9975 (0.3297)
Whole depth, cm (in.)	0.762 (0.300)
Addendum, cm (in.)	0.318 (0.125)
Chordal tooth thickness (reference), cm (in.)	0.485 (0.191)
Tooth width, cm (in.)	0.635 (0.25)
Pressure angle, deg	20
Pitch diameter, cm (in.)	8.890 (3.500)
Outside diameter, cm (in.)	9.525 (3.750)
Root fillet, cm (in.)	0.102 to 0.152 (0.04 to 0.06)
Measurement over pins, cm (in.)	9.603 to 9.630 (3.7807 to 3.7915)
Pin diameter, cm (in.)	0.549 (0.216)
Backlash reference, cm (in.)	0.0254 (0.010)
Tip relief, cm (in.)	0.001 to 0.0015 (0.0004 to 0.0006)

TABLE 2.—NOMINAL CHEMICAL COMPOSITION OF GEAR MATERIALS

Element	AISI 9310	VASCO matrix II	VASCO max 350	Nitralloy N
Carbon	0.1	0.51	0.01	0.24
Nickel	3.22	—	18.5	3.5
Chromium	1.21	4.0	—	1.18
Molybdenum	0.12	5.0	4.8	0.25
Cobalt	—	8.0	12.0	—
Manganese	0.63	0.15	0.05	0.55
Silicon	0.27	0.2	0.05	0.3
Sulfur	0.005	0.03	0.01	0.03
Phosphorous	0.005	0.03	0.01	0.03
Aluminum	—	—	0.1	1.08
Copper	0.13	—	—	—
Tungsten	—	1.0	—	—
Vanadium	—	1.0	—	—
Titanium	—	—	1.40	—
Boron	—	—	0.003	—
Calcium	—	—	0.05	—
Zirconium	—	—	0.02	—
Iron	Balance	Balance	Balance	Balance

TABLE 3.—HEAT TREATMENT FOR TEST GEARS

Nitralloy N
1. Normalize at 1200 K (1700 °F) for 4 hr, rough machine and copper plate. 2. Austenitize at 1170 K (1650 °F) for 2.5 hr and oil quench. 3. Temper to Rockwell C 30 to 36 at 964 K (1275 °F) for 5 hr and strip copper. 4. Finish machine, copper plate, stress relieve at 950 K (1250 °F) for 2 hr, strip copper plate. 5. Nitride at 800 K (980 °F) for sufficient time (50 to 100 hr) to obtain a case depth of 0.53 mm (0.021 in.) with a case hardness of Rc 65 to 70 and a core hardness of Rc 40 to 44. Maximum white layer shall be 0.013 mm (0.0005 in.).
VASCO Matrix II
1. Harden after rough machining by austenitizing at 1382 K (2030 °F) for 15 min, quench in salt bath at 880 K (1125 °F) and air cool to room temperature. 2. Triple temper (2 + 2 + 2 hr) at 820 K (1015 °F) as soon as the steel cools to 325 K (125 °F) from the quench. To minimize thermal shock, the steel shall be introduced into a cool tempering furnace, then advanced slowly to the tempering temperature. Hardness after tempering shall be Rockwell C 61 to 63. 3. Finish grind.
VASCO Max 350
1. Material shall be heat treated in a neutral salt bath or controlled atmosphere furnace. Do not anneal material as received. 2. Finish machine slightly oversize to allow for 0.025 mm (0.001 in.) shrinkage during age hardening. 3. Age harden to Rockwell C 59 to 60 for 3 hr at 770 K (925 °F) and air cool.
AISI 9310
1. Preheat in air and carburize at 1172 K (1650 °F) for 8 hr, air cool to room temperature. 2. Copper plate all over, reheat to 922 K (1200 °F) for 2.5 hr, air cool to room temperature. 3. Austenitize at 1117 K (1550 °F) for 2.5 hr and oil quench. 4. Sub cool to 180 K (–120 °F) for 3.5 hr. 5. Double temper (2 + 2) at 450 K (350 °F) hardness shall be Rc 59 to 62. 6. Finish grind and stress relieve at 450 K (350 °F) for 2 hr.

TABLE 4.—PROPERTIES OF SYNTHETIC PARAFFINIC LUBRICANT

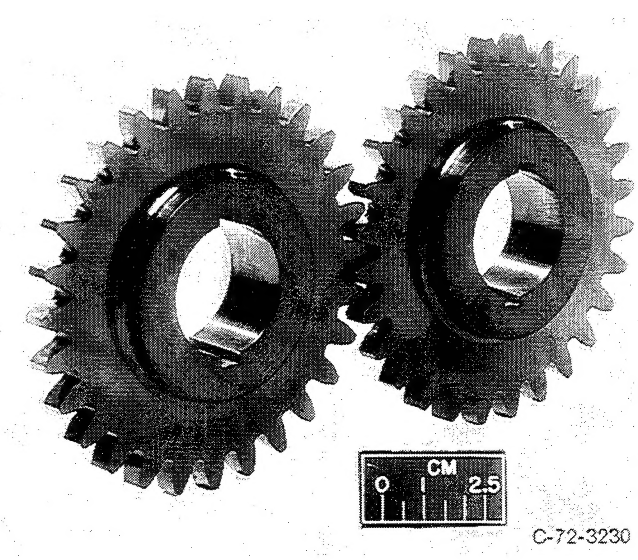
Additive	[a]Lubrizol 5002
Kinematic viscosity, cm^2/sec (cS) at—	
244 K (–20 °F)	2500×10^{-2} (2500)
311 K (100 °F)	31.6×10^{-2} (31.6)
372 K (210 °F)	5.7×10^{-2} (5.7)
477 K (400 °F)	2.0×10^{-2} (2.0)
Flash Point, K (°F)	508 (455)
Fire Point, K (°F)	533 (500)
Pour Point, K (°F)	219 (–65)
Specific Gravity	0.8285.
Vapor Pressure at 311 K (100 °F), mm Hg (or torr)	0.1
Specific Heat at 311 K (100 °F) J/kg k (Btu/lb °F)	676 (0.523)

[a]Additive, Lubrizol 5002 (5 vol%); content of additive: phosphorus, 0.7 wt%; sulphur, 13.4 wt%.

TABLE 5.—FATIGUE LIFE RESULTS FOR TEST GEARS

Gears	10-Percent life, cycles	50-Percent life, cycles	Slope	Failure index[a]	Confidence number,[b] percent
AISI 9310	21×10^6	45×10^6	2.4	19/20	—
VASCO matrix II	141×10^6	287×10^6	2.6	22/33	99
VASCO max 350	2.1×10^6	15.7×10^6	0.93	20/20	99
Nitralloy N	19×10^6	39×10^6	2.5	23/23	50

[a]Indicates number of failures out of number of test.
[b]Proability, expressed as a percentage, that the 10-percent life with the baseline AISI 9310 gears is either less than, or greater than, that of the particular lot of gears being considered.



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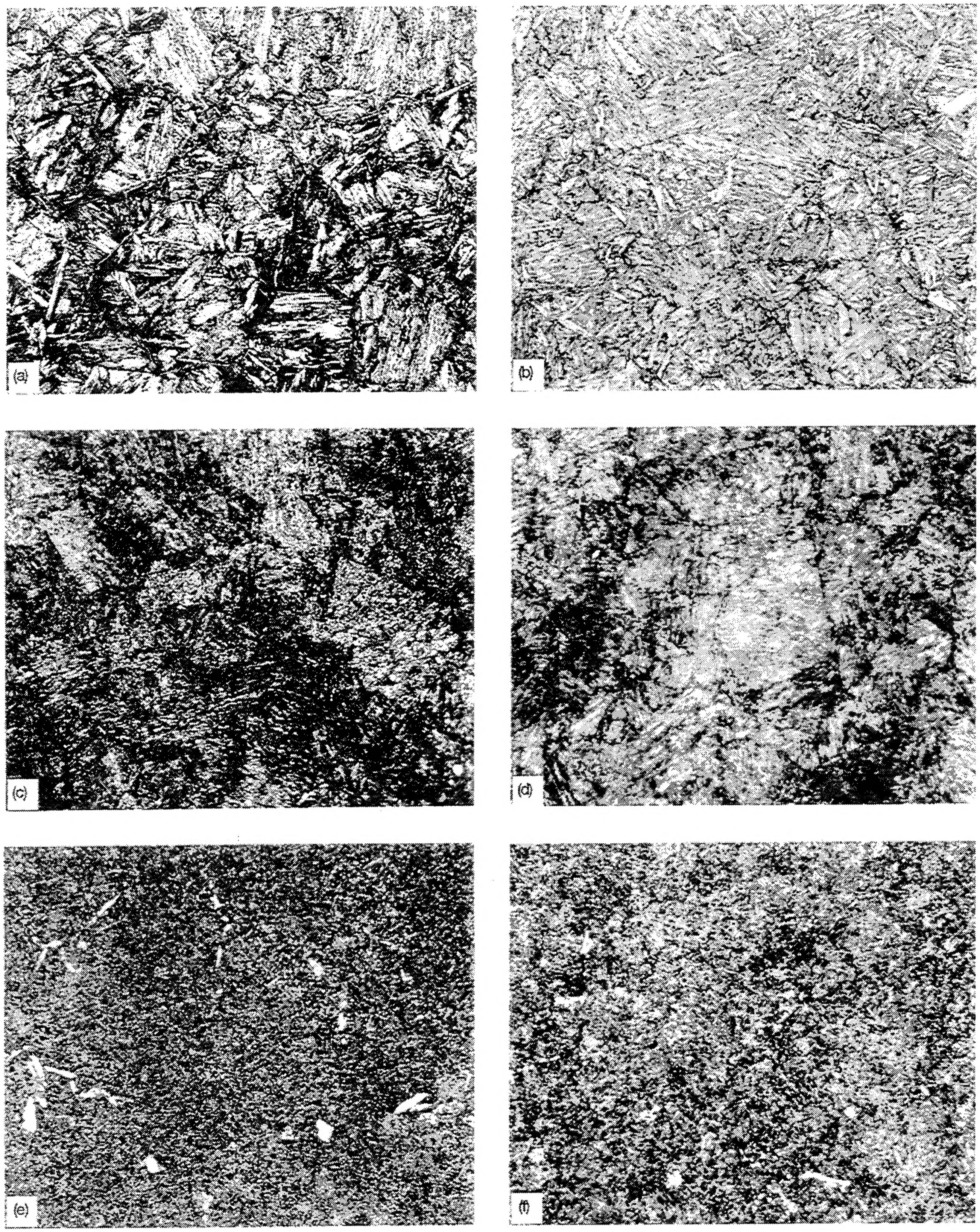


Figure 2.—Photomicrograph of case and core of test gears. (a) Case, (b) core; Nitralloy N. (c) Case, (d) core; VASCO Max 350. (e) Case, (f) core; VASCO Matrix II.

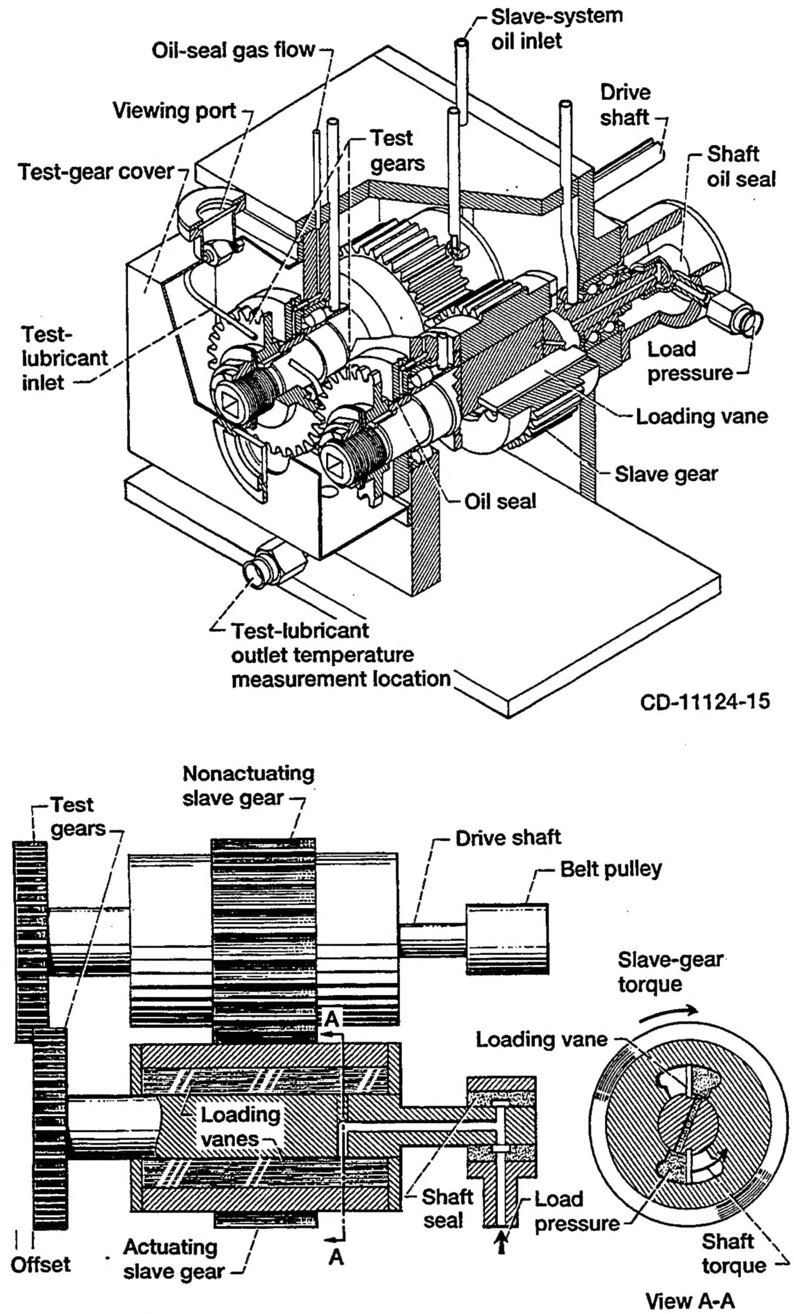


Figure 3.—NASA Lewis Research Center's gear-fatigue test machine. (a) Cutaway view. (b) Schematic diagram.

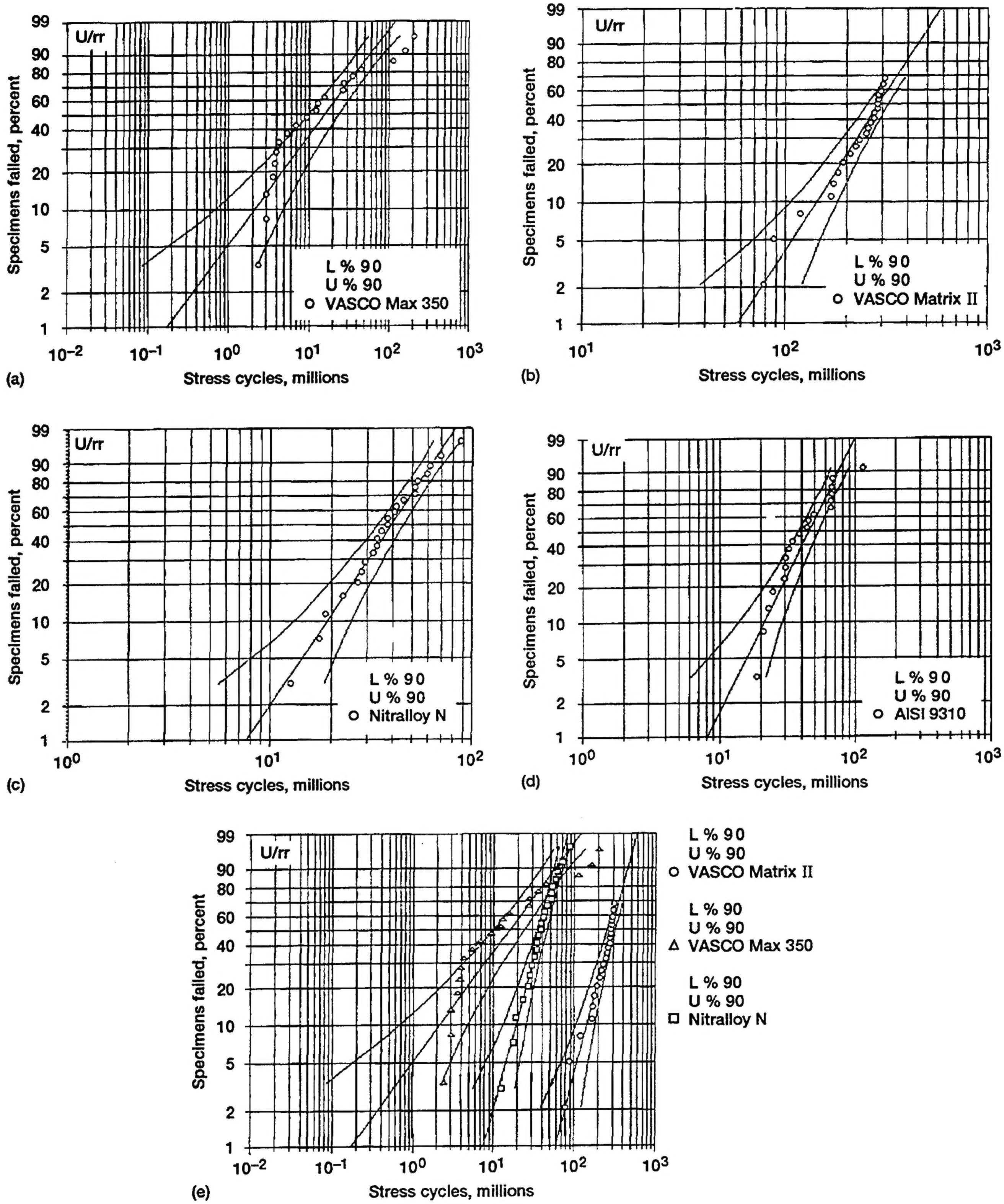
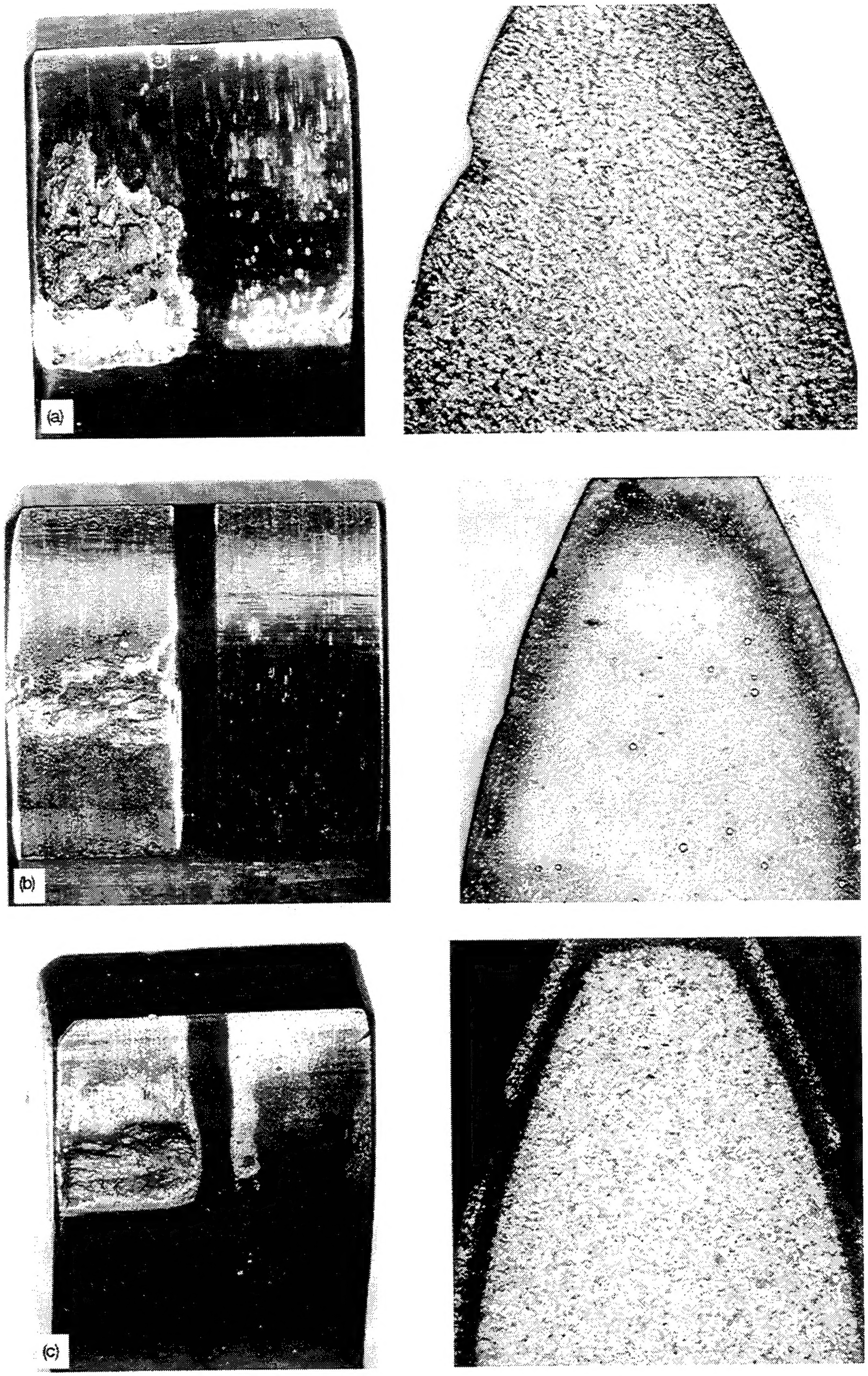


Figure 4.—Weibul plots of surface pitting lives of three high temperature gear materials compared with AISI 9310. Pitch diameter 8.39 cm (3.5 in.); speed 10 000 rpm; maximum Hertz stress 1.71 GPa (248 ksi); gear temperature 350 K (170 °F). (a) VASCO Max 350. (b) VASCO Matrix II. (c) Nitralloy N. (d) AISI 9310. (e) Summary.



Fatigue spall | Cross section

Figure 5.—Typical fatigue spall and cross section of three high temperature gear materials. (a) VASCO Max 350. (b) VASCO Matrix II. (c) Nitralloy N.

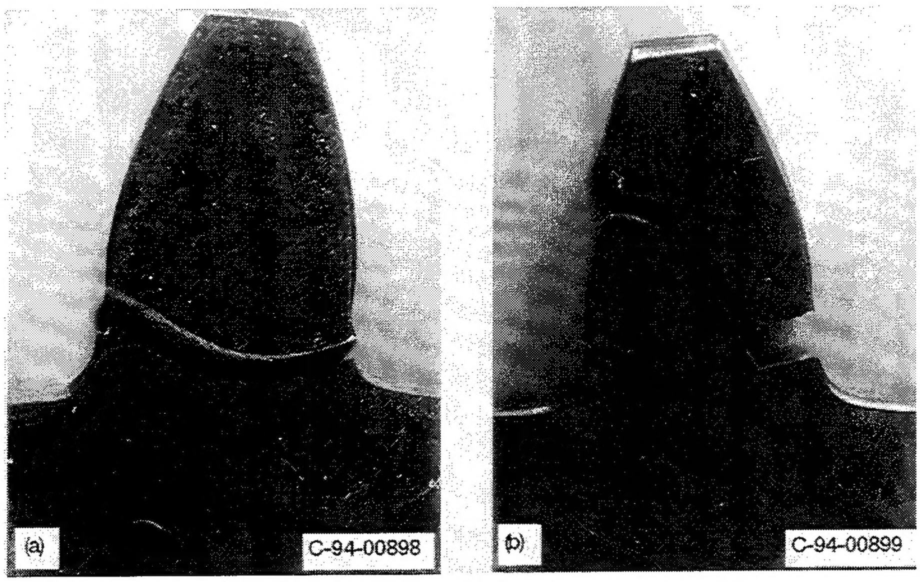


Figure 6.—Typical tooth fractures for two of the gear materials. (a) VASCO Max 350. (b) VASCO Matrix II.

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13. ABSTRACT ***(Maximum 200 words)***

Three high temperature gear materials were evaluated using spur gear surface fatigue tests. These materials were, VASCO max 350, VASCO matrix II, and nitralloy N and were evaluated for possible use in high temperature gear applications. The fatigue life of the three high temperature gear materials were compared with the life of the standard AISI 9310 aircraft gear material. Surface fatigue tests were conducted at a lubricant inlet temperature of 321 K (120 °F), a lubricant outlet temperature of 350 K (170 °F), a maximum Hertz stress of 1.71 GPa (248 ksi), a speed of 10 000 rpm and with a synthetic paraffinic lubricant. The life of the nitralloy N was approximately the same as the AISI 9310, the life of the VASCO max 350 was much less than the AISI 9310 while the life of the VASCO matrix II was several times the life of the AISI 9310. The VASCO max 350 also showed very low fracture toughness with approximately half of the gears failed by tooth fracture through the fatigue spall. The VASCO matrix II had approximately 10-percent fracture failure through the fatigue spalls indicating moderate to good fracture toughness.

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